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INFLUENCE OF NEIGHBORING STRUCTURES ON THE WIND PRESSURE ON TALL BUILDINGS

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ABSTRACT

Measurements have been made of the wind pressure over a model of the Empire State Building as affected by the presence of neighboring models simulating buildings which might be erected on the adjacent blocks. The object was to determine the shielding effect for different directions of the wind.

While the pressure on certain faces of the building was increased somewhat by the presence of the neighboring structures, the resultant of pressure on the windward face and suction on the lee face was decreased. The decrease was greatest when the interfering structure was close by and directly upstream. The height shielded was not so great as the height of the interfering structure.

Shielding may produce a variation in the twisting moment about a vertical axis at different levels. The stresses set up by this loading may require consideration in special cases.

CONTENTS

I. INTRODUCTION

One of the most important problems, from a structural standpoint, in the design of a tall building is the wind-bracing system. Experiment as well as theory is required as a guide in the designing of the various members and their connections of a structure that is to be both safe and rigid.

Just what wind pressure a building may have to withstand, no one knows. The wind pressure depends in the first instance on the maximum wind velocity encountered. Much valuable information on the maximum wind velocities observed in different parts of the country is published yearly by the United States Weather Bureau in Washington, and these data should be consulted when a tall building is to be designed. The main Committee for Standardization of Building Codes in the Netherlands [2] recommends that the pressure

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[2] Het Bouwbedrijf, Aug. 26, 1932, and Oct. 21, 1932. Wind-belasting op Bouwerken, by R. L. A. Shoemaker and I. Wouters.

to be used in the design of buildings shall vary with the locality in which the building is to be erected. A chart has been made showing what maximum wind velocities may be expected in any part of the Netherlands.

The wind pressure also depends on the shape of the structure and on its exposure. Although the individual factors are not separately discussed, the building codes of some of the larger cities modify the requirements to satisfy surrounding conditions of exposure and protection. In some instances there is a variation according to height (reflecting the change of wind velocity with height), while in others a certain constant pressure is to be used above a given distance from the ground. The building ordinance of Amsterdam (Netherlands) provides for a wind pressure of 21 to 51 lb per sq. ft. according to exposure. The Prussian regulations provide for a variation of 15 to 45 lb per sq. ft. depending upon the height, exposure, and location of the building. At a recent meeting of the structural division of the American Society of Civil Engineers [3] it was recommended that the wind pressure to be finally adopted in any case should be based not only on information furnished by observation stations situated in the locality concerned, but also on such other factors as shielding and the effects of turbulence. The belief still exists that 20 lbs. per sq. ft for the first 500 ft, increased by 2 lb per sq ft for each additional 100 ft, is generally adequate for purposes of design.

The relation between wind pressure and wind speed has been most often studied by wind-tunnel experiments on models.[4] A recent investigation of the wind pressure on a model of the Empire State Building in the 10-foot wind tunnel at the Bureau of Standards [5] showed that for this building the pressure was $0.0038V^2$ lb per sq ft where V is the wind speed in mph.

It is the purpose of this paper to show how the distribution of pressure on the same building would be affected by the existence of nearby buildings, using models to simulate certain specified conditions.

II. MEASUREMENTS OF WIND PRESSURE

1. APPARATUS

The model of the Empire State Building and the method of making measurements of wind pressure have been fully described in Research Paper No. 545. Figure 1 is a photograph of that and the other two models used in the present study. They were mounted in the 10-foot wind tunnel of the Bureau of Standards on a platform simulating the ground. The three models are designated *A*, *B*, and *C*, and are shown in their relative positions in figure 3. The model of the Empire State Building (model *A*) and the distances between the models are to a scale of 1 to 250 and represent a possible future condition at the intersection of Fifth Avenue and Thirty-third Street in New York City.

[3] Civil Engineering, March 1933.

[4] For a full discussion of the use of models and the principles of similitude, refer to: Osborne Reynolds, Scientific Papers, vol. 2, paper no. 61, p. 524; Prof. Stokes, On the Effect of Internal Friction on the Motion of the Pendulum, Trans. Cambridge Phil. Soc. 1851–56; Alton C. Chick and John R. Freeman, Dimensional Analysis and The Principle of Similitude as Applied to Hydraulic Experiments with Models, A.S.M.E. Proceedings, 1929; E. Buckingham, Model Experiments and the Forms of Empirical Equations, A.S.M.E. Spring Meeting, 1915; Benj. Groat, Trans. A.S.M.E. vol. 96.

[5] H. L. Dryden and G. C. Hill, B.S. Jour. Research, vol. 10. (RP 545), April 1933.

Model *A* was made of aluminum, models *B* and *C* of wood finished to a smooth surface. All three models were mounted on a circular plate which in turn was placed on a platform, the front edge of which was brought to a knife-edge thickness. The whole group was arranged so that the top of model *A* and the platform were equidistant from the tunnel axis. By means of ball bearings under the circular plate the entire group could be rotated through 360°, so that observations could be made for any desired direction of wind relative to the group. When face *D* (fig. 3) of model *A* was set normal to the direction of the wind, the direction was called 0°. This corresponds to the wind blowing up Fifth Avenue. Angles increase as the plate is rotated clockwise. Readings were taken at angles of 0°, 20°, 40°, 50°, 70°, and at angles 90°, 180°, and 270° greater than each of these, but only certain of these at 40°, 160°, and the pairs 0°, 180°, and 90°, 270° are discussed in this paper.

Only model *A* had pressure holes, or observation stations. There were 17 holes at each of the 3 levels corresponding to the seventy-fifth, fifty-fifth, and thirty-sixth floors of the actual building, these levels being denominated *A*, *B*, and *C*, respectively (figs. 1 and 2). The pressure holes were mainly on two faces of the model, so that it was necessary to rotate model *A* through 180° with respect to the other models in order to make observations at all angles.

Model *B* represents a building 640 feet high facing the Empire State Building on Fifth Avenue and extending back along Thirty-third and Thirty-fourth Streets about 200 feet. The setbacks and size of tower are, with some slight modifications, in accordance with the recommendations of the Regional Plan of New York and Its Environs.[6]

The setbacks of model *C* along Fifth Avenue are the same as those of the Empire State Building, and the top of *C* is at the height of the middle line of pressure holes in *A* (figs. 1 and 3). The first makes it possible to study the effect, if any, on the pressure on face *A*, model *A*, when the wind is parallel to that face, and the corresponding face of the screening object (*C*) is, at every level, in the same plane as face *A*, model *A*. The second was for the purpose of determining whether the shielding effect extended to the full height of the interfering structure.

2. METHOD OF PRESENTING DATA

When the air is at rest, as we experience it in a room with all openings closed, or in a calm, the pressure exerted by it is of equal intensity in all directions. When the air has been set in motion, an object moving with the speed and in the direction of the wind is also subject to a uniform distribution of pressure. The magnitude of this pressure is called the static pressure, or the normal atmospheric pressure. When there is a relative motion between the object and the air, the intensity of pressure is changed. The change may be either an increase or a decrease with respect to the static pressure, depending upon the direction of the wind with respect to some reference line fixed in the object. In general, it may be said that the air pressure on objects exposed to the wind will be increased on the windward side and decreased on the leeward side. At some points there will be no change from the static pressure.

[6] Thomas Adams, Limiting the Size of Buildings, Civil Engineering, October 1932.

Thus when the wind blows against a surface, p, the force per unit of area at any point may be regarded as consisting of two parts—the static pressure p_s and the increase, or wind pressure, p_w, which

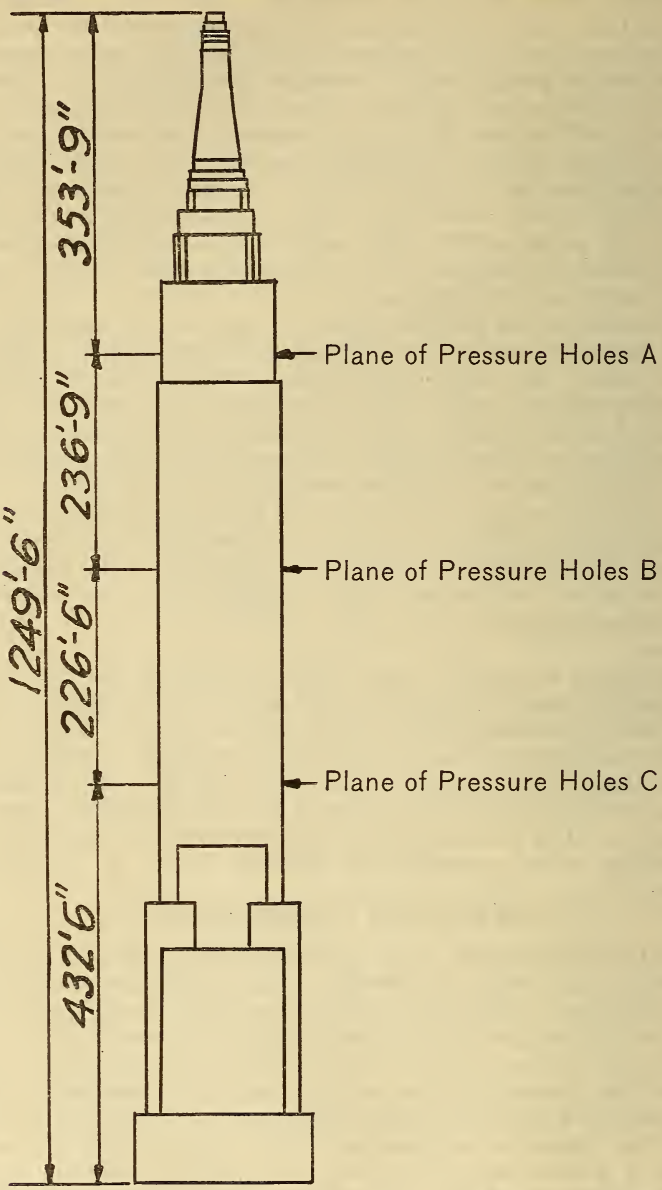

FIGURE 2.—*Location of sections A, B, and C on the Empire State Building.*

equals $p-p_s$. The wind pressure may be either positive or negative or zero. The maximum possible increase in pressure due to the wind is called the velocity pressure and is $q=\frac{1}{2}\rho V^2$, where ρ is the density of the air, and V the velocity of the wind.

FIGURE 1.—*Models mounted on platform in the wind tunnel.*

The pressure holes are drilled in brass plugs which appear as dark spots at 3 levels. The other dark spots are brass screws holding the model together.

It is customary in aerodynamic work to measure the wind pressure in terms of the velocity pressure q, to express the results in terms of the coefficient p_w/q. The coefficients thus obtained are independent of the units of measurement so long as the units used are consistent, and in many cases are independent of both the wind speed and the size of the model; in such cases data obtained from the model may be applied directly to the prototype. When the ratio of the wind pressure to the velocity pressure is not a constant we have what is called a scale effect. The pressure coefficient is then a function of the Reynolds number, $\frac{VL\rho}{\mu}$, where L is a dimemsion fixing the scale, and μ is the viscosity of the air; and unless the scale effect is small it is difficult to infer from the observations the pressures to which the prototype will be subjected at a given wind velocity. Usually, however, the scale effect is small, the average value of the pressure coefficient differing from its extremes by only 2 or 3 percent, which is well within the factor of safety used in design.

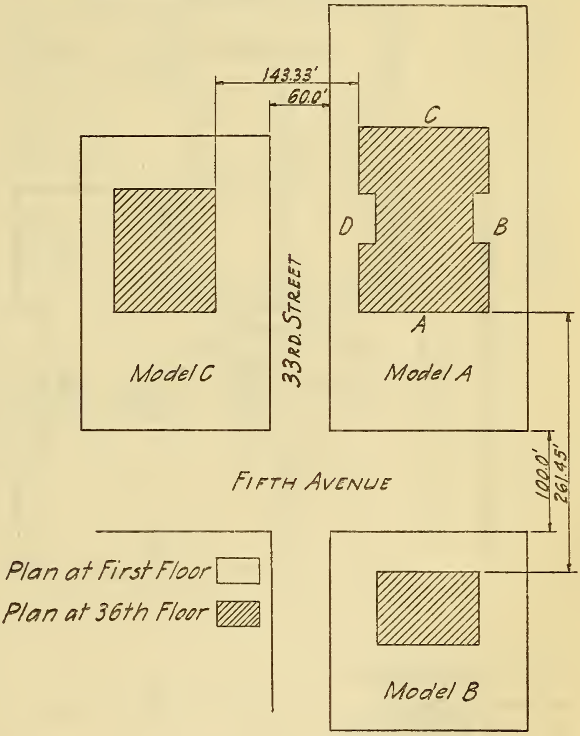

FIGURE 3.—*Plan, to scale, of assumed location which was reproduced on a scale of 1:250 on the platform in the wind tunnel.*

3. RESULTS

In this investigation, measurements were made at three wind speeds, 40, 60, and 80 ft/sec. The pressure coefficients p_w/q for each speed were computed as explained in Research Paper 545.

It was observed in a number of instances that the pressure coefficient varied systematically when the speed was changed; in other words, there was some scale effect. No broad statement can be made that applies to all stations and directions of the wind; in general, the pressures tend to be somewhat greater at the higher speeds, and in few instances does the extreme difference exceed $0.1q$. For about 40 percent of the total number of observations, the individual readings did not depart from the mean by more than $0.02q$.

As an illustration of the magnitude of the scale effect found, consider the observations at section A, well above levels B and C, with wind at 160° (fig. 4). It will be observed that the pressure distribution curves for the three speeds resemble each other very closely. Some of the differences shown are due not to variations in scale effect, but to unavoidable limitations in the precision of the measurements. Although there is somewhat greater evidence of scale effect than in the similar measurements given in Research Paper 545 for model A alone, it is still so small that it is considered negligible for

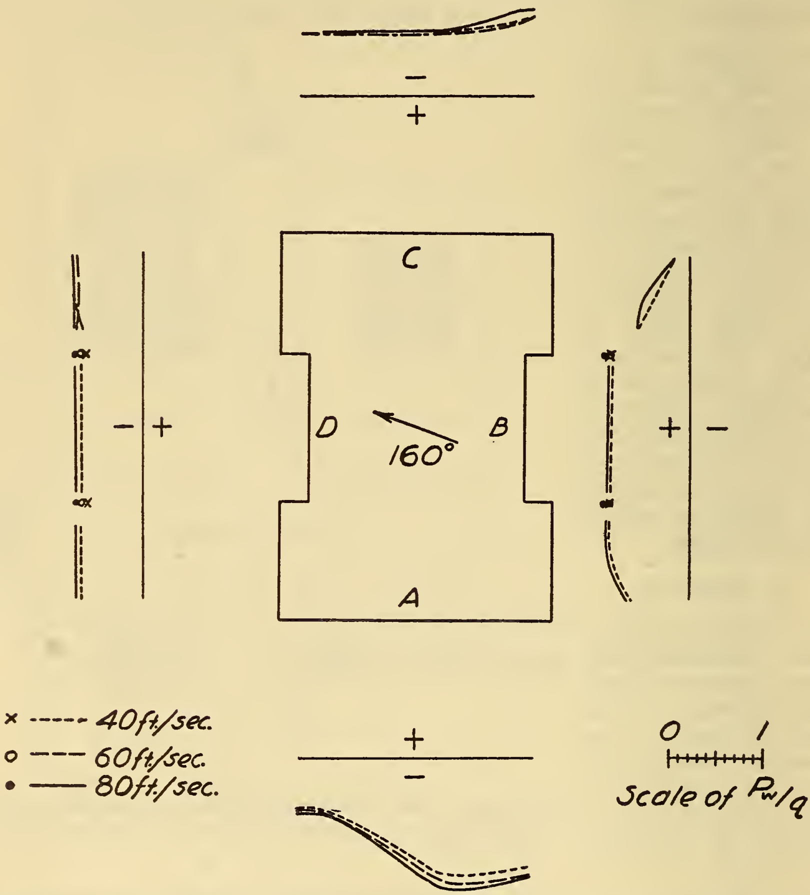

Figure 4.—*Distribution of pressure at section A for the speeds indicated, setting 160°. Wind in direction of arrow.*

purposes of design. Consequently, it has been ignored in the cases now to be considered, and the slightly differing coefficients corresponding to the several wind velocities have been averaged. The average alone is given and discussed.

The effect of the presence of the neighboring models B and C on the pressure on model A is indicated by the change in the distribution of the pressure over A when the direction of the wind is changed by 180°; an obstruction that is on the lee side of A for one of those directions will be on the windward for the other. Data for forces

normal to the wind directions are given in table 1 (page 112) for two such pairs of wind directions.

For wind along Fifth Avenue, directions 0° and 180°, the change in the average pressure coefficient on going from 180° (*C* to lee) to 0° (*C* to windward) was for the windward face of *A*: An

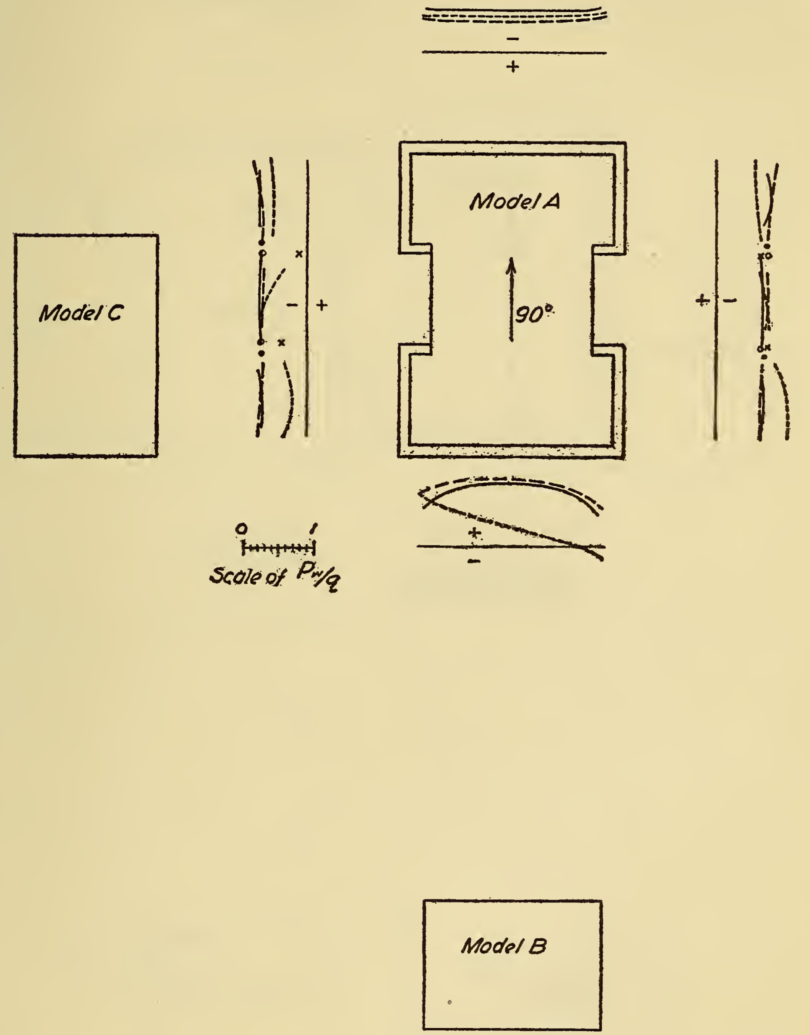

FIGURE 5.—*Distribution of pressure for setting 90°. Wind in direction of arrow.*

The pressures are measured from the static pressure (in the absence of all models) as base and expressed as ratios to the velocity pressure. Positive ratios are plotted inward from the thin base lines to the scale shown. Minus signs denote that the pressure is lower than the static pressure. The circles and crosses give the values at stations 10, 14, 27, and 31 on the side walls of the embrasures. (See figs. 9, 10, 11.)

increase from 0.71 to 0.79, or 11 percent at the upper row of holes; at the middle row, a decrease of 7 percent; and at the lower row a decrease from 0.77 to −0.54, or 170 percent. For the same change in the wind (180° to 0°) the change in the suction (negative-pressure

coefficient) on the lee face of *A* was: A decrease of 21 percent at the upper row, of 14 percent at the middle row, and an increase of 7 percent at the lower row. The combined effect of pressure on the wind-

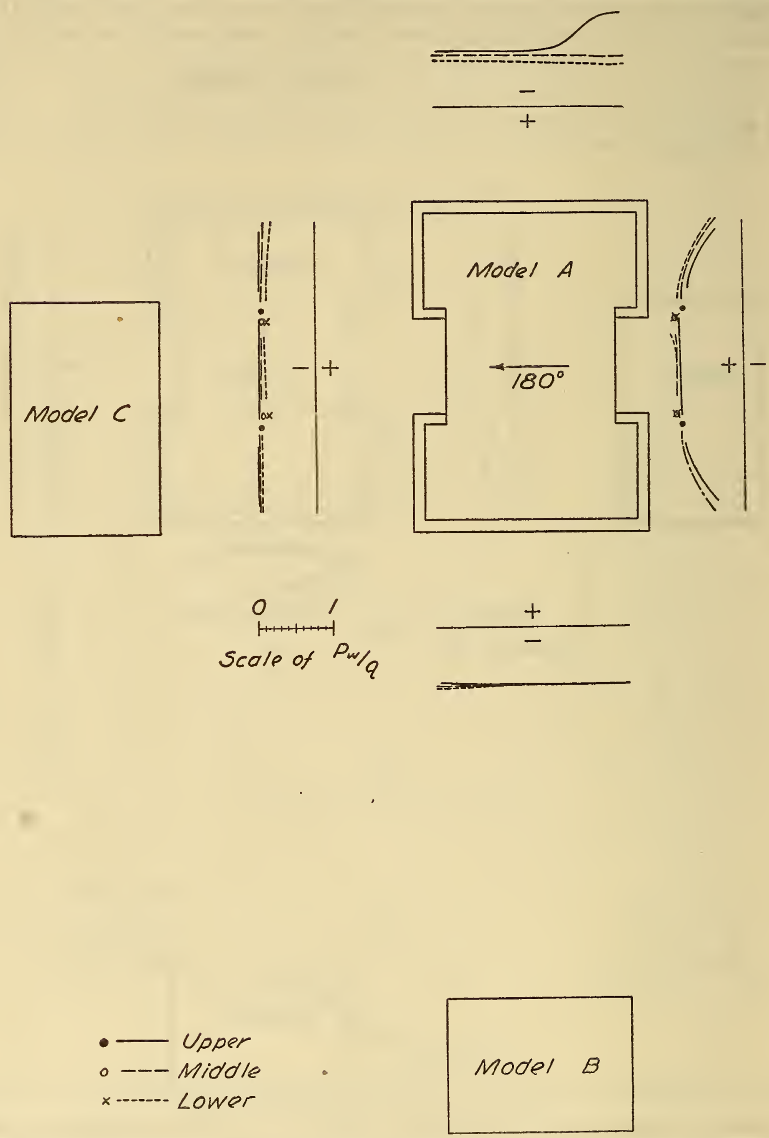

Figure 6.—*Distribution of pressure for setting 180°. Wind in direction of arrow.*

The pressures are measured from the static pressure (in the absence of all models) as base and expressed as ratios to the velocity pressure. Positive ratios are plotted inward from the thin base lines to the scale shown. Minus signs denote that the pressure is lower than the static pressure. The circles and crosses give the values at stations 10, 14, 27, and 31 on the side walls of the embrasures. (See figs. 9, 10, 11.)

ward face and suction on the lee face decreases by 6, 11, and 87 percent at the upper, middle, and lower row of holes when the wind changes from 180° to 0°. The distribution of pressure in these cases is shown in figures 6 and 7.

Similarly for wind along Thirty-third Street. When the wind changes from 270° (*B* to lee) to 90° (*B* to windward) the average pressure coefficient for the three rows of holes in the order upper,

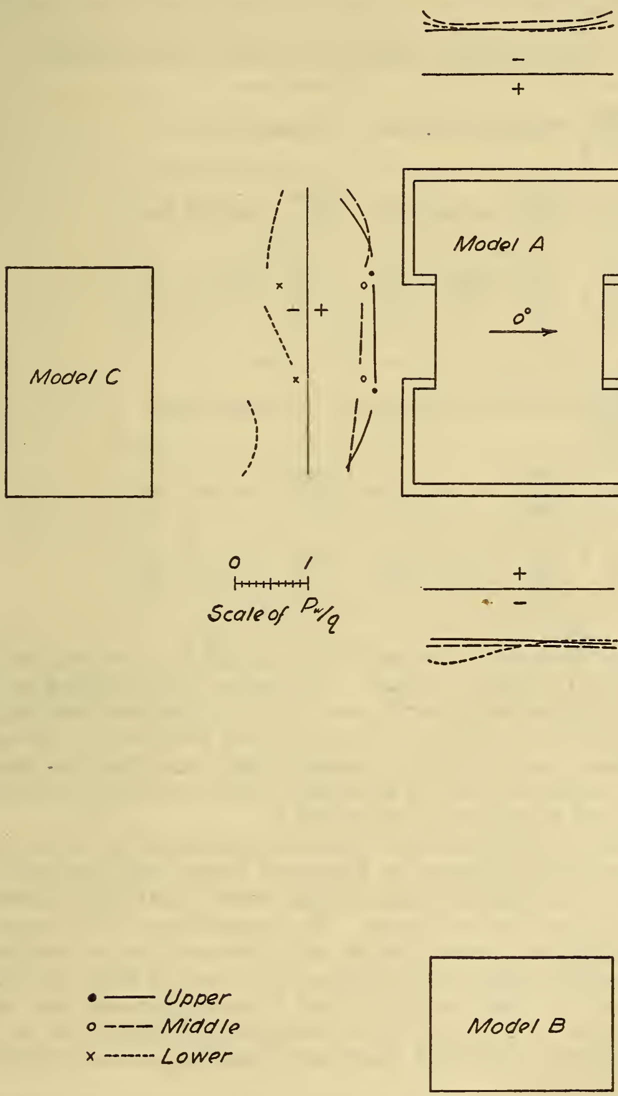

FIGURE 7.—*Distribution of pressure for setting 0°. Wind in direction of arrow.*

The pressures are measured from the static pressure (in the absence of all models) as base and expressed as ratios to the velocity pressure. Positive ratios are plotted inward from the thin base lines to the scale shown. Minus signs denote that the pressure is lower than the static pressure. The circles and crosses give the values at stations 10, 14, 27, and 31 on the side walls of the embrasures. (See figs. 9, 10, 11.)

middle, and lower on the windward face of *A* increases by 4 percent, increases by 7 percent, and decreases by 64 percent; and the suction (negative coefficient) for the holes on the lee face of *A* decreases by

15 percent, by 14 percent, and by 2 percent. The combined effect of pressure and suction decreases by 6 percent, by 2 percent, and by 39 percent. The distribution of pressure for the 90° direction is shown in figure 5.

Table 1.—*Average pressure coefficients for certain wind directions*

Wind direction	0° (model *C* to windward)			180° (model *C* to lee)		
Level	Windward face	Lee face	Total	Windward face	Lee face	Total
A	0.785	−0.601	1.386	0.709	−0.762	1.471
B	.699	−.633	1.332	.752	−.737	1.489
C	−.537	−.729	.192	.767	−.679	1.446

Wind direction	90° (model *B* to windward)			270° (model *B* to lee)		
Level	Windward face	Lee face	Total	Windward face	Lee face	Total
A	0.750	−0.616	1.366	0.724	−0.722	1.446
B	.832	−.482	1.314	.778	−.563	1.341
C	.279	−.529	.808	.779	−.538	1.317

It will be noted that the shielding due to model *B* is not as great as that due to model *C*, which is closer. Moreover the shielding at the middle row is comparatively small, even with buildings extending to the height of that row of holes. It was in fact observed by threads that the wind blew over the top of model *C* and was diverted downward along the windward face of *A*, thence back to *C* along the floor, and thence upward along the lee of model *C*.

A comparison of the figures for the force coefficients in table 1 for 180° and 270° with those given in Research Paper 545 for model *A* alone mounted on the floor of the tunnel, shows that the values in table 1 are from 5 to 8 percent lower. A comparison with the results in table 1 of additional measurements at a few stations on model *A* alone mounted on the platform indicates that there is some shielding present at 90° and 0° when models *B* and *C* are at the side and rear, amounting to 3 or 4 percent. The remaining difference is to be ascribed to a difference between floor and platform representation of the ground effect.

It should be noted here that the changes in the average coefficients for the separate faces are of limited significance, since the base pressure is taken more or less arbitrarily as the static pressure when no buildings are present. A change in the base pressure would affect the forces on the separate faces, although the sum of the effects on the windward and lee faces would be unchanged. In an actual building, the interior pressure is not necessarily equal to the static pressure used as the base pressure from which other pressures are measured in the model experiments. Hence the loadings on individual wall panels or faces of the building may differ by a uniformly distributed loading

from that tabulated. The value of the interior pressure does not, however, affect the total forces and moments on the building.

From the data obtained, the loading on the building may be studied in as much detail as desired. As an example, the distribution of pressure for a wind direction of 40° is shown in figure 8, and the

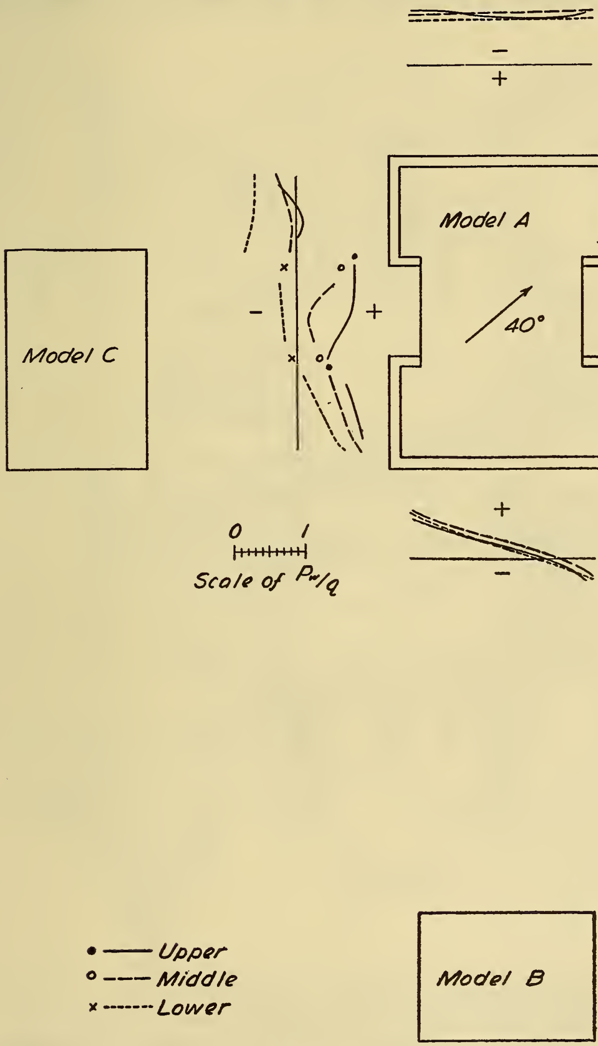

FIGURE 8.—*Distribution of pressure for setting 40°. Wind in direction of arrow.*

The pressures are measured from the static pressure (in the absence of all models) as base and expressed as ratios to the velocity pressure. Positive ratios are plotted inward from the thin base lines to the scale shown. Minus signs denote that the pressure is lower than the static pressure. The circles and crosses give the values at stations 10, 14, 27, and 31 on the side walls of the embrasures. (See figs. 9, 10, 11.)

resultant loading is analyzed for the three levels in figures 9, 10, and 11. The diagrams in these figures are force diagrams for the full scale building.

The procedure by which the several pressure coefficients were combined in obtaining the total force is this. Imagine a strip 1 foot wide

taken around the entire building, the center of its width coinciding with the line of pressure holes. On each face of the building draw vertical lines midway between the holes. These lines together with the edges of the faces divide the strip into a series of panels, in each of which is a single pressure hole. The pressure coefficient for each hole is multiplied by the area of its panel, and the product is regarded as

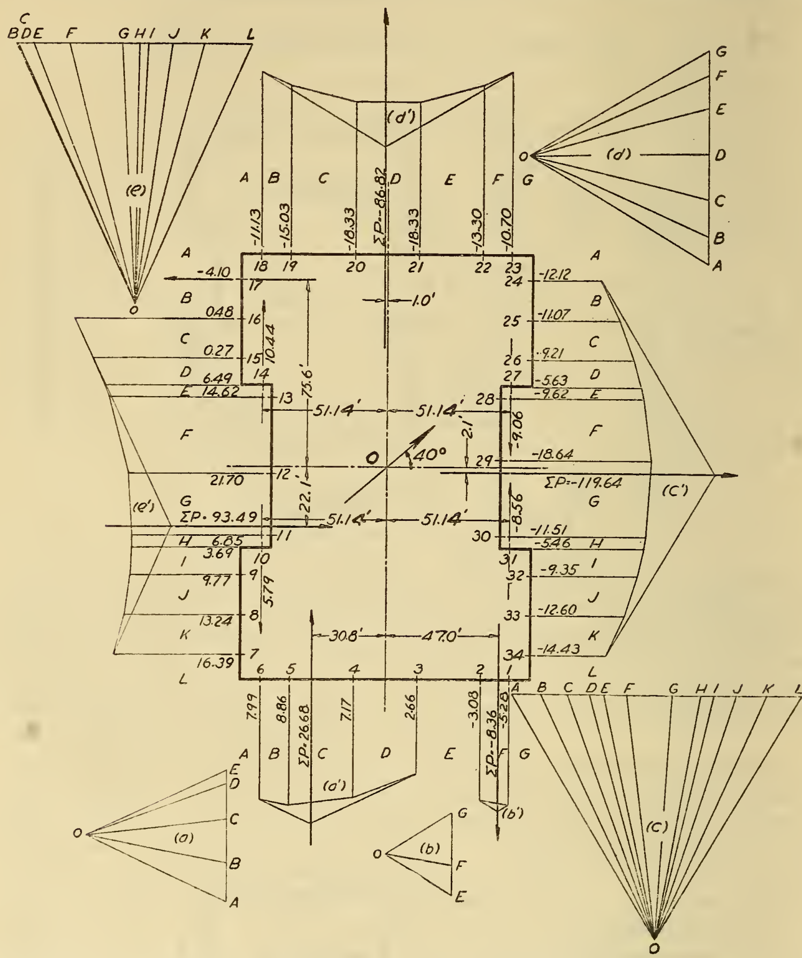

FIGURE 9.—*Graphical representation of pressures exerted on building at section A at setting 40°. Wind in direction of arrow.*

The numbers on the lines through the pressure stations are the values of the force acting on the panel divided by the velocity pressure. The resultants on the several faces are determined graphically in the auxiliary diagrams, *a*, *a'*, *b*, *b'*, etc.

the ratio of the actual force on that panel to the velocity pressure q. Although the holes are not in all cases at the centers of their respective panels, the error so caused is small.

These products are entered along lines through the pressure stations perpendicular to the faces. The resultant forces and the lines of application of the resultants on each face have been constructed graphically. Where positive and negative values are found on the same face, the resultant is given for each separately.

It is evident that when the wind pressure in a given horizontal plane is unevenly distributed on the sides of a building there is produced a torsional effect about a vertical axis in addition to the overturning moment. For the case illustrated, the twisting moment M

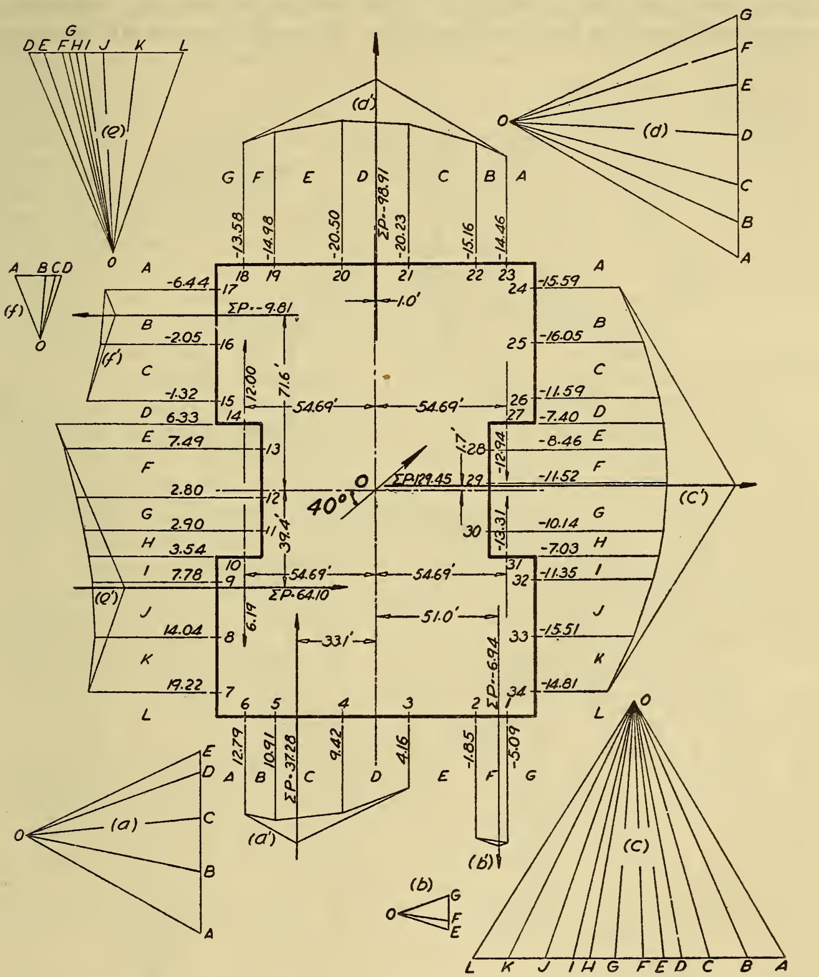

FIGURE 10.—*Graphical representation of pressures exerted on building at section B at setting 40°. Wind in direction of arrow.*

The numbers on the lines through the pressure stations are the values of the force acting on the panel divided by the velocity pressure. The resultants on the several faces are determined graphically in the auxiliary diagrams, *a*, *a′*, *b*, *b′*, etc.

may be obtained by taking moments about O, the trace of the vertical axis of the building, clockwise moments being positive.

$$\begin{aligned}\text{Level } A \text{ (fig. 9) } M/q = & -93.49\times 22.1-4.10\times 75.6+86.82\times 1.00\\ & -119.64\times 2.1+8.36\times 47.0+26.68\times 30.8\\ & -5.79\times 51.14+10.44\times 51.14+9.06\times 51.14\\ & -8.56\times 51.14\\ = & -1{,}062 \text{ ft.}^3\end{aligned}$$

Similarly at level B, $M/q = -1{,}221$ ft.^{3} and at level C, $M/q = -2{,}180$ ft^3

If the wind velocity is known, the actual moment per ft. of height can be found by multiplying the above figures by the velocity pressure. For example, the velocity pressure for a wind velocity of 90 mph is 20.72 lb per sq ft and hence the moment per ft height at level C is $2{,}180 \times 20.72 = 45{,}170$ lb ft. The resultant force may readily be computed from the data in figure 11. It is 140.3 q=2,907 lb per ft

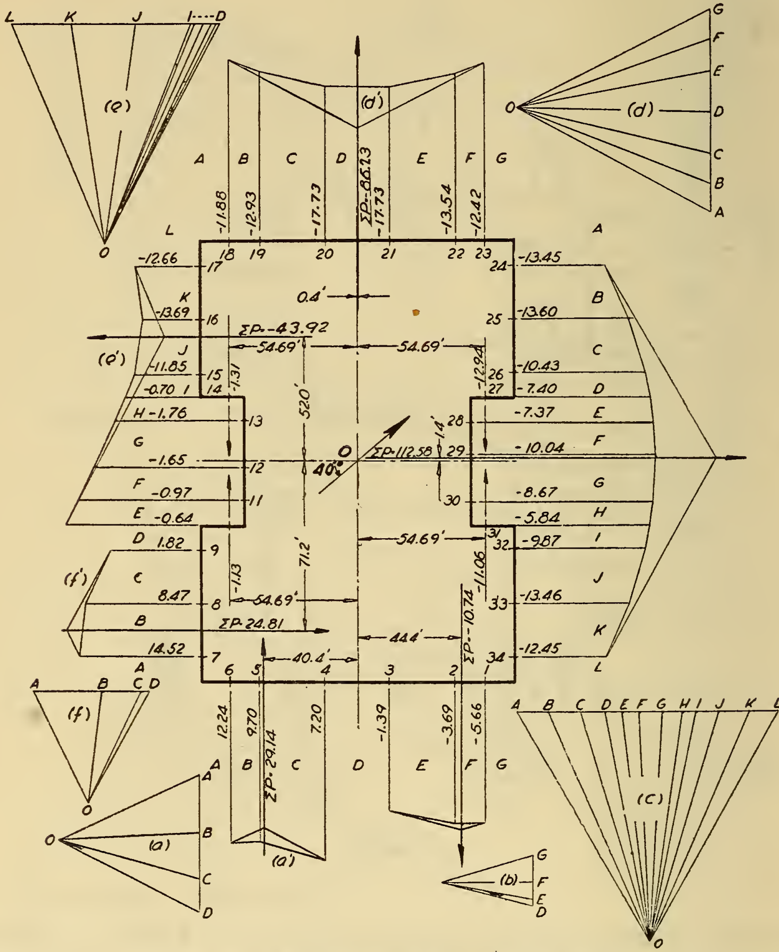

FIGURE 11.—*Graphical representation of pressures exerted on building at section C at setting 40°. Wind in direction of arrow.*

The numbers on the lines through the pressure stations are the values of the force acting on the panel divided by the velocity pressure. The resultants on the several faces are determined graphically in the auxiliary diagrams, *a*, *a′*, *b*, *b′*, etc.

of height. The displacement of the resultant force from the axis of the building is therefore 45,170/2,907 = 15.5 ft.

It will be noted that the torque at level C is nearly double that at levels A and B, an effect produced by the presence of the other models.

Analysis of the loading at other angles may be made in a similar manner.

III. ANALYSIS OF THE RESULTS WITH REFERENCE TO THE DESIGN OF TALL BUILDINGS

The measurements show that the wind pressure is distributed over the building in a manner quite different from the uniform loading commonly assumed; that the wind pressure varies with the direction of the wind and depends on the interference set up by existing nearby buildings; and that in addition to shear and overturning moment, the wind produces a torsional moment about a vertical axis. Under these conditions of loading, the columns are subjected to direct, bending, shearing, and torsional stresses, and the girders are subject to direct, bending, and shearing stresses. It is evident that considerable attention should be given to the design of the columns and of the connections between the floor framing, especially the girders and spandrel sections, and the columns. No connection should be relied upon to perform two functions simultaneously without investigation of its capability to perform both functions simultaneously.

In the design of the wind-bracing system the question of rigidity should be carefully considered. The author believes that all panels should be braced to withstand wind pressure from any direction, in particular that end panels should have diagonal or sway bracing, or knee bracing at each column and that the wind bracing should not be confined to the center of high towers. He believes that where girder connections are designed to withstand moment and shear due to wind loads, wide wing-plate and angle combinations should be used instead of the socalled "split flange I-beam method." It is realized that this practice increases the amount of millwork, but as a compensation, the tonnage of steel is reduced because of the reduction of the effective lengths of columns and girders and hence in the required section areas in computing the stresses due to column and bending action.

The author believes that the effects of the torsional moment about a vertical axis are of considerable importance. If the moments at each plane were equal, the problem would be analogous to that of a cantilever beam loaded uniformly but eccentrically. When the distribution of force is not uniform, as when shielding is present, the torsional moments at the several elevations are unequal. A change in the moment in passing from one story to another is due to the action of externally applied wind moment, and the resultant loading of the building is analogous to that of a cantilever beam, nonuniformly and eccentrically loaded. The planes of the flooring system tend to become distorted and to take the shape of a warped surface. Due to the rigidity of the flooring systems commonly used (steel encased in concrete), the stresses in the columns are likely to be the more important.

As an illustration of a failure of a building in a high wind which probably was a failure in torsion, mention may be made of the Meyer-Kiser building in Miami, Fla. A special committee of the American Society of Civil Engineers [7] was appointed to investigate the results of the storm in which this building failed. The top of the building was twisted [8] in a clockwise direction about 1°. Most of the twisting probably occurred between the fifth and thirteenth floors. Little damage

[7] Papers and Discussions A.S.C.E., vol. 54, pt. 2, p. 1757, 1928.
[8] Engineering News Record, vol. 97, pp. 586 and 624, 1926.

was done to floors and ceilings. The committee attributes the twisting in large measure to the fact that one end of the building was stiffer than the other.

The author is indebted to the Bureau of Standards and its director, Dr. Lyman J. Briggs, for the facilities placed at his disposal, to Dr. Hugh L. Dryden, chief, aerodynamical physics section, for helpful criticism and suggestions, and to Mr. W. H. A. Boyd for assistance in making observations and recording data.

WASHINGTON, October 14, 1933.